ADMI IJST International Journal Science and Technology
IJST Vol 4 No. 3 | November 2025 | ISSN:2828-7223 (print), ISSN: 2828-7045 (online), Page. 75-88

Internal Force Analysis on Simple Truss Structure: Evaluation of the Cramer's Rule Method

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Article History
Received : December 11, 2025
Accepted : December 22, 2025
Published : December 23, 2025
Available Online :
December 23, 2025

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Cite This Article:
Rif'atul Khusniah, Cahyani, K. N., & Yoganata, Y. S. (2025). Internal Force Analysis on Simple Truss Structure: Evaluation of the Cramer's Rule Method. International Journal Science and Technology, 4(3), 75–88.

DOI:
https://doi.org/10.56127/ijst.v4i3.2408

Abstract: This study analyzes internal forces in simple truss structures using Cramer's Rule, a method for solving systems of linear equations based on the force balance at each node. The system is converted into a coefficient matrix and solved to calculate the internal forces in each member. The study also examines the impact of numerical errors, such as rounding and coefficients near zero, which can degrade accuracy. The results show that Cramer's Rule performs well for small structures but becomes increasingly sensitive to errors as the system complexity increases. This highlights the need for numerical methods in structural analysis, especially for large or complex structures. The study uses simple truss structures as a model, which may not fully represent real-world structures that are larger, asymmetrical, or subject to dynamic loads. While Cramer's Rule is useful for minor problems and educational purposes, more advanced methods, such as Gaussian elimination or finite element analysis, are required for real-world applications. The findings show that Cramer's Rule is effective for simple models in teaching, but caution is needed when applying it to more complex systems.

Keywords: Internal force analysis, Truss Structure, Cramer's Rule, Numerical Errors.

INTRODUCTION

In civil engineering, structural analysis is crucial for the design and evaluation of the strength and stability of buildings and other structures. One method for analyzing internal forces in truss structures is Cramer's Rule, a linear-algebra technique for solving systems of linear equations. Although Cramer's Rule has been widely used in basic mathematics, its application in structural analysis in civil engineering remains limited, even though it is effective for solving the system of equations derived from force equilibrium at each joint of a structure.

A frame is a structural element composed of thin profiles connected at both ends. Channels, angles, metal rods, and *wooden struts are materials* often used in building construction. The ends of the elements are usually bolted or welded to plates called a *gusset plate* (Hibbeler, 2020).

A truss structure, also known as a hinged joint structure, is a structure consisting of straight members connected using friction joints (Miura & Pellegrino, 2020). Structural analysis is the study of how a structure responds to external forces such as loads, temperature variations, and supports (Hassan & Saeed, 2024).

Internal force analysis of simple truss structures is crucial in civil engineering, particularly for ensuring structural stability and safety. In this context, the use of numerical methods, such as Cramer's Rule, is crucial for simplifying and accelerating the analysis process and reducing reliance on manual analysis, which is more prone to human error. Through internal force analysis, truss design can be made more efficient and economical. Research (Simanjuntak et al., 2023) shows that truss analysis using the gusset equilibrium method and the Ritter method does not show any differences in calculation results.

By ensuring that each structural element only receives forces appropriate to its capacity, excessive use of materials can be avoided, not only reducing costs but also minimizing the waste of natural resources and supporting the principle of sustainability in construction.

One of the numerical techniques that can be used to solve the system of linear equations that describe the balance of forces in internal force analysis structures is the Gauss-Jordan method (Nasmirayanti et al., 2022). Internal force analysis for a truss structure with 15 members and 9 nodes using the Gauss-Jordan method provides effective results (Khusniah et al., 2025).

To provide a broader context for the numerical methods used in truss analysis, several recent studies have explored alternative and advanced computational techniques for determining internal forces in truss structures. (Sun et al., 2025) proposed a recursive force transfer method to analyze internal forces in trusses, offering a complementary perspective to classical equilibrium methods. Likewise, (Ha et al., 2025) introduced an index-based neural network model that demonstrates the potential of machine learning frameworks in static truss analysis, particularly under extensive computational requirements.

Furthermore, comprehensive deformation analysis via mode shape decomposition has been applied to plane trusses, underscoring the value of advanced numerical analysis in capturing structural behavior (Wang et al., 2022). In addition, literature reviews that aggregate multiple methods, including stiffness matrix approaches and software-assisted analyses, further support the need for robust numerical techniques in truss force calculation (Oktaviani et al., 2023). Recent developments in symbolic matrix structural analysis provide analytical foundations that reinforce the theoretical basis for matrix-based solution techniques like Cramer's rule in engineering applications (Plevris & Ahmad, 2025).

Although this method is known for its efficiency, it faces a common challenge: numerical errors that can arise during the calculation process (Marpaung et al., 2025). These errors can impact the accuracy of the analysis results, especially when dealing with complex structures or when the number of elements in the truss increases.

The purpose of this study is to evaluate the effectiveness of Cramer's Rule method in the analysis of internal forces in simple truss structures, as well as to analyze how numerical errors can affect the results of internal force calculations. This research is expected to contribute to the development of more efficient and accurate methods in structural engineering.

RESEARCH METHOD

This study analyzes the effectiveness of Cramer's rule for calculating internal forces in simple truss structures. The purpose of this analysis is to examine how Cramer's Rule, a method for solving systems of linear equations, can be applied to structural analysis, particularly for simple truss models commonly used in civil engineering education. This method is tested under the assumption that the truss structures are linear-elastic and symmetrical, which simplifies the model and makes it more manageable for educational purposes.

The assumption of linear elasticity means that the truss elements behave according to Hooke's Law (Gilbert, 2022), where the deformation is directly proportional to the applied force, and there is no permanent deformation. The assumption of symmetry reduces the number of equations and simplifies the overall analysis by making the system more straightforward to solve. These assumptions are made to focus on applying Cramer's Rule to relatively simple structural problems, thereby facilitating evaluation of the effectiveness and limitations of this method in determining internal forces without introducing the complexities of non-linear behavior or irregular loading conditions.

Thus, the research method using Cramer's Rule to solve the system of equations derived from the force equilibrium at each node of a truss structure helps assess the accuracy and practicality of this approach for basic structural analysis tasks. The simplified model allows for more precise conclusions about the method's applicability in educational contexts and its limitations when applied to more complex, real-world structures. Recent studies demonstrate continued interest in Cramer's Rule as a method for solving systems of linear equations across disciplines. (Supriadi et al., 2025) found that the use of Cramer's Rule significantly improved mathematical thinking and student outcomes in solving fixed pulley problems.

This study was conducted by designing and implementing a basic mathematical model to calculate the internal forces in a simple triangular truss using Cramer's Rule method. Cramer's Rule is applied to this structure by constructing a system of linear equations that describes the balance of forces at each node. The analysis steps carried out in this study are:

1. Developing a mathematical model for a simple truss structure
   a. Identifying the elements of a simple truss structure
   b. Compile force balance equations for each connection (node)
   c. Composing a system of linear equations
   d. Converting a system of equations into matrix form
2. Implementation of Cramer's rule method to analyze simple truss structures
   a. Forming a coefficient matrix from the system of force equations formed
   b. Solve the system of equations using Cramer's rule to obtain the internal forces in each truss.

Analysis of the Influence of Numerical Errors

One of the significant concerns when applying Cramer's Rule in structural analysis is the potential for numerical errors, which can arise due to rounding errors, truncation errors, or computational limitations. Several studies on Cramer's Rule provide an overview of its application to more complex linear systems, including quaternion matrices, which are relevant to force calculations in truss structures. (Song et al., 2018) explain the application of Cramer's Rule to Quaternion Matrix Equation Systems, which helps in understanding how this method is applied in the context of non-commutative matrices.

Furthermore, (Song et al., 2011) also made significant contributions to the understanding of unique solutions to constrained matrix equation systems using Cramer's Rule, which improves the accuracy and precision in solving linear equations related to frame structures. Meanwhile, (Kyrchei, 2021) explains the sensitivity analysis to numerical errors in determinant representations for solving systems of equations. As highlighted by previous studies, such as (Sun et al., 2025), numerical methods are often prone to instability when dealing with larger, more complex systems of equations. This issue is particularly relevant when solving problems involving large determinants or requiring numerous iterations, which can introduce significant errors in the final results.

RESULT AND DISCUSSION

The simple truss structure used in this study consists of15 children And 9 nodes, as shown in Figure 1. This structure receives vertical loads at several evenly distributed nodes: 1 ton at the ends and 2 tons at the midspan points. With hinge and roller supports at each end, the structure is assumed to be statically determinate. Based on the balance of the total vertical force, the support reactions are obtained:

$$SUN_{in} = RB_{in} = \frac{1}{2}(1 + 2 + 2 + 2 + 2 + 2 + 1) = 6\ ton$$

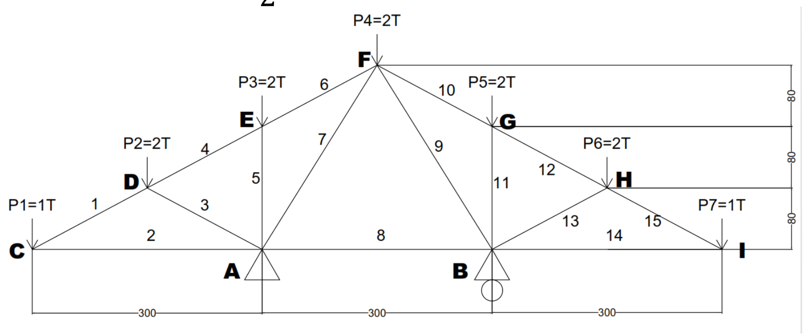


Figure 1. Simple Truss Structure

This shows that the system is symmetric, so the internal force on the left side of the rod is equal to the internal force on the right side; only the direction of the force (pulling/compressing) may differ.

The identification of the bar and node elements in a truss structure with 15 bars and 9 nodes is denoted by bar symbols.$s_1, s_2, \cdots, s_{15}$and knot$J_A, J_B, \cdots, J_I$. Each node J_i connected by several rods, and the forces acting on each node must satisfy the force balance. Based on the concept of statics of the truss, each node must satisfy:

$$\sum F_x = 0 \quad (1)$$

$$\sum F_y = 0 \quad (2)$$

Where F_x And F_{and}each is an external force acting on the node in the horizontal and vertical directions.

The next step is to form a system of linear equations that relates the internal forces in the rod to the external forces at the nodes. Each rods_i contribute to two nodes, and these contributions are included in the system of equations. The resulting system of linear equations will have dimensions 18.×1, because there are 18 external forces (9 nodes with 2 directions) and 15 internal forces in the truss. Because the truss is symmetrical, the calculations are performed at the nodes.

$J_A = J_B, J_C = J_I, J_D = J_H, J_{AND} = J_G.$

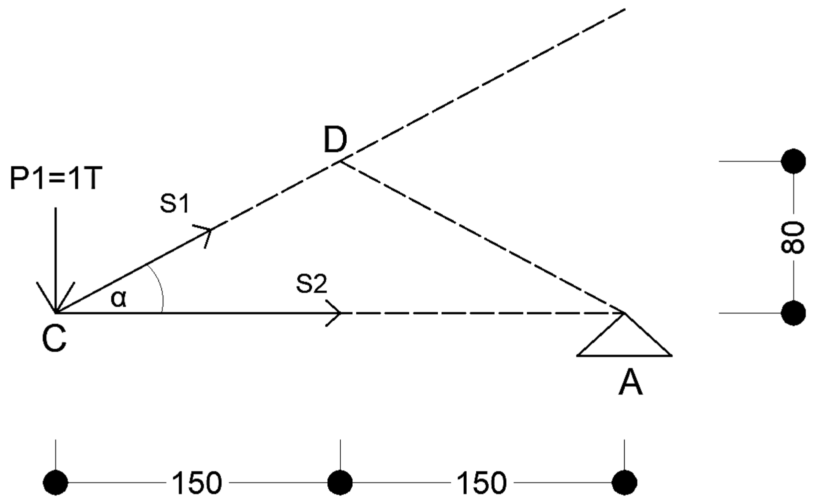
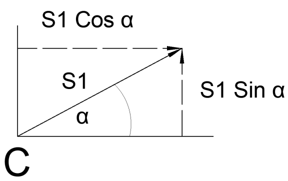


Figure 2. A-A Section

The J_C node is symmetric with the J_I node.

Node-connected stems J_C: s_1, s_2

Node-connected stems J_I: s_{14}, s_{15}



$$\tan\alpha = \frac{80}{150} = 0{,}5333$$

$$\alpha = \arctan\frac{80}{150} = 28{,}0724°$$

$$\cos\alpha = \cos 28{,}0724° = 0{,}8824$$

$$\sin\alpha = \sin 28{,}0724° = 0{,}4706$$

$$F_{Cy} = -1 + s_1 \sin\alpha = 0 \quad (3)$$

$$F_{Cy} = 0{,}4706\, s_1 = 1$$

$$F_{Cx} = s_1 \cos\alpha + s_2 = 0 \quad (4)$$

$$F_{Cx} = 0{,}8824\, s_1 + s_2 = 0$$

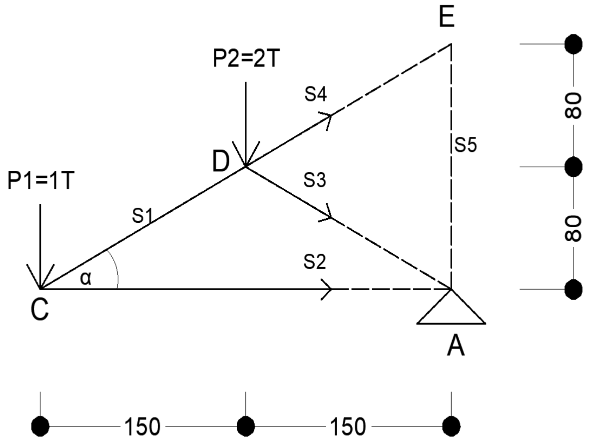
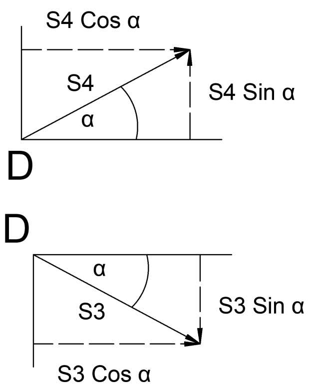


Figure 3. b-b Section

The J_D node is symmetric with the J_H node.

Node-connected stemsJ_D: s_1, s_3, s_4

Node-connected stemsJ_H: s_{12}, s_{13}, s_{15}



$$F_{Dy} = -2 - s_1 \sin\alpha - s_3 \sin\alpha + s_4 \sin\alpha = 0 \quad (5)$$

$$F_{Dy} = -s_1 \sin 28{,}0724° - s_3 \sin 28{,}0724° + s_4 \sin 28{,}0724° = 2$$

$$F_{Dy} = -0{,}4706\, s_1 - 0{,}4706\, s_3 + 0{,}4706\, s_4 = 2$$

$$F_{Dx} = -s_1 \cos\alpha + s_3 \cos\alpha + s_4 \cos\alpha = 0 \quad (6)$$

$$F_{Dx} = -s_1 \cos 28{,}0724° + s_3 \cos 28{,}0724° + s_4 \cos 28{,}0724° = 0$$

$$F_{Dx} = -0{,}8824\, s_1 + 0{,}8824\, s_3 + 0{,}8824\, s_4 = 0$$

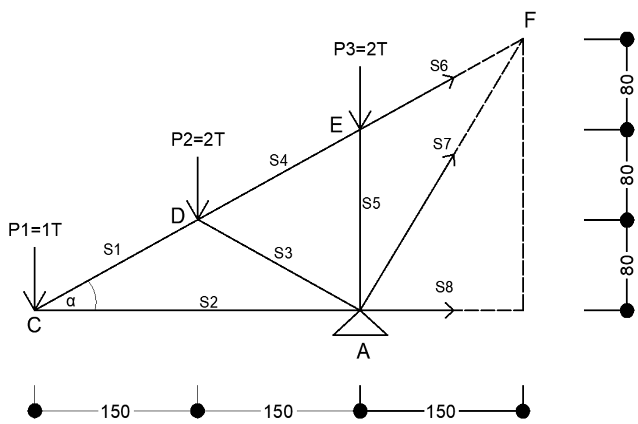
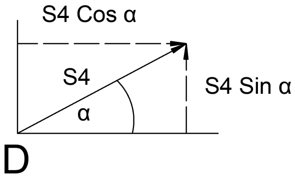


Figure 4. C-c Section

The J_E node is symmetric with the J_G node.

Node-connected stemsJ_{AND}: s_4, s_5, s_6

Node-connected stemsJ_G: s_{10}, s_{11}, s_{12}



$$F_{Ey} = -2 - s_4 \sin\alpha - s_5 + s_6 \sin\alpha = 0 \quad (7)$$

$$F_{Ey} = -0{,}4706\, s_4 - s_5 + 0{,}4706\, s_6 = 2$$

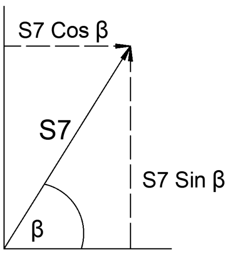
$$F_{Ex} = -s_4 \cos\alpha + s_6 \cos\alpha = 0 \quad (8)$$

$$F_{Ex} = -0{,}8824\, s_4 + 0{,}8824\, s_6 = 0$$

Node J_A is symmetric with node J_B

Node-connected stemsJ_A: s_2, s_3, s_5, s_7, s_8

Node-connected stemsJ_B: $s_8, s_9, s_{11}, s_{13}, s_{14}$



$$\tan\beta = \frac{240}{150}$$

$$\beta = \arctan\frac{240}{150} = 57{,}9946°$$

$$\cos\beta = \cos 57{,}9946° = 0{,}5300$$

$$\sin\beta = \sin 57{,}9946° = 0{,}8480$$

$$F_{Ay} = R_{AV} + s_3 \sin\alpha + s_5 + s_7 \sin\beta = 0 \quad (9)$$

$$F_{Ay} = 6 + 0{,}4706\, s_3 + s_5 + 0{,}8480\, s_7 = 0$$

$$F_{Ay} = 0{,}4706\, s_3 + s_5 + 0{,}8480\, s_7 = -6$$

$$F_{Ax} = s_2 + s_3 \cos\alpha - s_7 \cos\beta - s_8 = 0 \quad (10)$$

$$F_{Ax} = s_2 + 0{,}8824\, s_3 - 0{,}5300\, s_7 - s_8 = 0$$

The matrices multiplied for equations (3) to (10) are as follows:

$$\begin{bmatrix} \sin\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \cos\alpha & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\sin\alpha & 0 & -\sin\alpha & \sin\alpha & 0 & 0 & 0 & 0 \\ -\cos\alpha & 0 & \cos\alpha & \cos\alpha & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\sin\alpha & -1 & \sin\alpha & 0 & 0 \\ 0 & 0 & 0 & -\cos\alpha & 0 & \cos\alpha & 0 & 0 \\ 0 & 0 & \sin\alpha & 0 & 1 & 0 & \sin\beta & 0 \\ 0 & 1 & \cos\alpha & 0 & 0 & 0 & -\cos\beta & -1 \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \\ s_7 \\ s_8 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 2 \\ 0 \\ 2 \\ 0 \\ -6 \\ 0 \end{bmatrix}$$

Where $\sin \sin \alpha = 0{,}4706$, $\cos \cos \alpha = 0{,}8824$, $\sin \sin \beta = 0{,}8480$, And $\cos \cos \beta = 0{,}5300$so that the matrix is obtained

The system of linear equations above will be solved using **Cramer's Rule**with the following solution:

$$\begin{bmatrix} 0,4706 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0,8824 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0,4706 & 0 & -0,4706 & 0,4706 & 0 & 0 & 0 & 0 \\ -0,8824 & 0 & 0,8824 & 0,8824 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0,4706 & -1 & 0,4706 & 0 & 0 \\ 0 & 0 & 0 & -0,8824 & 0 & 0,8824 & 0 & \square\square \\ 0 & 0 & 0,4706 & 0 & 1 & 0 & 0,8480 & 0 \\ 0 & 1 & 0,8824 & 0 & 0 & 0 & -0,5300 & -1 \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \\ s_7 \\ s_8 \end{bmatrix}$$

$$= \begin{bmatrix} 1 \\ 0 \\ 2 \\ 0 \\ 2 \\ 0 \\ -6 \\ 0 \end{bmatrix}$$

Based on the calculation results using Cramer's rule above, the results are compared with the results of the truss analysis calculations using the Ritter method results (Khusniah et al., 2025) and the following results are obtained:

Table 1. Comparison of Internal Force Magnitude (Ton)

Knot	Method Ritter	Cramer's Rule	Difference	Information
1=15	2,128	2,125	0,003	Pull
2=14	-1,875	-1,875	0,000	Press
3=13	-2,128	-2,125	0,003	Press
4=12	4,251	4,249	0,002	Pull
5=11	-2,000	-2,000	0,000	Press
6=10	4,247	4,249	0,002	Pull
7=9	-3,538	-3,538	0,000	Press
8	-1,875	-1,875	0,000	Press

The results obtained using Cramer's rule are in close agreement with those obtained using Ritter's method. From the analysis results above, it can be seen that the maximum difference is only 0.003 tons, which indicates that:

1. Calculation analysis using Cramer's Rule can be considered valid and accurate.
2. The system of equations has been correctly arranged according to the calculation rules of the frame structure.
3. The analysis results show that the structure is symmetrical and the load is well distributed.

Advantages of Cramer's Method

Cramer's method offers several significant advantages for internal force analysis in simple truss structures. The main advantage lies in its ability to yield exact results, provided that the determinant of the coefficient matrix is nonzero. This accuracy is evident in the member force calculations, where the values obtained by Cramer's method are nearly identical to those obtained by Ritter's method. For example, the member force $_1$ obtained is 2,125 tons (pull), only 0.003 tons different from the Ritter method result of 2.128 tons. A similar thing is seen in the stems_2 which shows style **–1,875 tons (press)**, which is in complete agreement with the results of Ritter's method. This agreement indicates that Cramer's method can yield precise solutions for simple static structures.

The next advantage is that the Cramer method's calculation procedure is systematic, direct, and easy to verify. The preparation of the coefficient matrix based on the force balance equation at each node allows researchers to carry out consistency checks in stages, starting from the formulation of equations (3) to (10), until the formation of the 8×8 matrix used to solve the bar forces.s_1 until s_8The symmetrical nature of structures such as those in this study further supports the effectiveness of Cramer's method, as the number of equations can be reduced without eliminating the structure's internal force characteristics. Thus, this method remains efficient and highly suitable for small- to medium-scale truss studies.

Limitations of Cramer's Method

Despite offering high accuracy, Cramer's method has several limitations that must be considered. The main limitation is its inefficiency in solving systems of equations with a large number of variables. When the matrix dimension exceeds 10×10, computing the determinant becomes computationally intractable and impractical to perform manually. For asymmetric truss structures or those consisting of tens or hundreds of members, Cramer's method requires significantly more time than Gaussian elimination or modern matrix algorithms used in computer-based structural analysis.

Furthermore, Cramer's method is susceptible to errors in the typing or input of coefficients. A small error in a single element of the coefficient matrix can lead to a distorted determinant that affects the entire system solution. This presents a challenge in the analysis of large-scale structures, where the large number of equations increases the risk of errors. Furthermore, Cramer's method does not provide additional information, such as the matrix's numerical stability, the degree of conditioning, or the diagnosis of system irregularities factors that are essential in modern matrix methods to ensure the accuracy and reliability of structural analysis results.

To validate the data and results, it is crucial to cross-check the findings against established methods, such as Gaussian elimination or Ritter's method, to ensure consistency and identify potential discrepancies. Additionally, using computational tools such as MATLAB or Excel can help minimize human error, verify numerical results, and provide insights into the system's numerical stability and conditioning, thereby ensuring more reliable results, particularly for larger, more complex structures.

Implications of Analysis Results

The analysis results show that Cramer's method produces internal forces that are highly consistent with those obtained by the Ritter method. The maximum difference of 0.003 ton indicates that the coefficient matrix derived from the nodal equilibrium equations is mechanically consistent. This shows that Cramer's method can serve as a powerful verification tool for simple truss structures, especially those with symmetric properties, as in this study.

From the structural behavior perspective, the internal forces obtained also show a logical pattern and correspond to the direction of loading. For example, the bars$_1$ show a pulling force of 2,125 tons, whereas the stems 7 with stand the most significant compressive force, namely –3,538 tons**.** This tensile–compressive force pattern accurately depicts the force distribution mechanism in a truss structure with uniform vertical loading. This accuracy ensures that the results can be used for further analysis, such as material capacity verification, member cross-sectional size design, or structural integrity evaluation.

From a methodological perspective, the results of this study confirm that Cramer's method remains highly relevant and can serve as a learning tool and a manual verification tool in structural analysis. In an academic context, this method provides a deeper understanding of the relationship between the equilibrium equations for forces at nodes and the resultant forces in the members. Furthermore, Cramer's method can serve as a comparative tool to validate the results of structural analysis software, particularly for simple models used for training or introductory structural analysis.

CONCLUSION

Based on the analysis of internal forces in simple truss structures using the Cramer Method and compared with the Ritter Method, several important conclusions were obtained as follows:

1. This study successfully demonstrated that Cramer's Rule is an effective method for solving internal force analysis in simple truss structures. The results obtained using Cramer's Rule were in close agreement with those derived from the Ritter method, with a maximum difference of only 0.003 tons, indicating the validity and accuracy of the method.
2. The resulting internal force patterns demonstrate consistency with the geometric configuration and loading direction. For example, members s_1 and s_4 act in tension with forces of 2.125 tons and 4.249 tons, respectively, while members s_2 and s_7 act in compression with forces of –1.875 tons and –3.538 tons, respectively. This consistency strengthens the validity of the analysis and demonstrates that the internal force distribution conforms to that of a symmetrical truss.
3. The findings suggest that Cramer's Rule is an effective and efficient method for solving small-scale problems in structural analysis, particularly when the system of equations is relatively simple and the determinant is sufficiently large to avoid numerical instability.
4. Cramer's Rule becomes inefficient when applied to large systems of equations, especially in cases where the matrix dimension exceeds 10x10. As the matrix size increases, calculating the determinant becomes computationally expensive and practically difficult to perform manually.
5. Overall, the results of this study confirm that the Cramer Method is a valid, accurate, and relevant analytical approach for simple truss structures. The obtained internal force values can be used as a basis for further studies such as bar dimension planning, material strength evaluation, or deformation analysis. Furthermore, this method can serve as both a conceptual and a verification tool for matrix-stiffness method-based structural analysis.

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